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*ON KATHODE RAYS AND SOME RELATED PHENOMENA.**

I.

AMONG the branches of physical investigation that have recently shown especial activity, few occupy a more prominent position at the present time than those that are related to the electrical discharge in rarefied gases. This is true not only because of the rapid development of the subject, but also because of the far reaching importance of the results, and the influence which they seem destined to exert upon widely different branches of physics. When I learned that I was to have the privilege of addressing you to-day, it appeared to me that I could not better utilize the opportunity than by briefly recalling the progress in this subject during the last few years, and calling attention to some of the results that we may reasonably hope for in the future. The whole subject of vacuum tube discharge is, of course, too large to be treated in the brief space of an hour. I shall therefore confine myself to one of its more important subdivisions, namely, the phenomena and theory of the kathode rays.

Of the many beautiful and interesting phenomena that accompany the electrical discharge in rarefied gases, certainly none has attracted such widespread attention as

* Address of the Vice-President and Chairman of Section B (Physics) of the American Association for the Advancement of Science, given at the New York meeting.

the kathode rays. Since their discovery by Plücker in 1859, and the first systematic study of their properties by Hittorf and Crookes, the importance of a more complete understanding of their nature has been generally recognized, and many eminent physicists have made them the subject of extended experimental investigation. In consequence, our knowledge of the kathode rays has progressed during the last few years with startling rapidity. To make clear how great the progress has been, let us consider first the condition of the subject of 1890, at which time the theory of vacuum tube phenomena was just beginning to take systematic and consistent form.

Almost from the time of the first discovery of the kathode rays, widely different opinions had been held regarding their nature. According to one view, the kathode rays were to be regarded as disturbances in the ether, propagated in a manner somewhat analogous to that in which light is transmitted. The rays were not considered as essential to the passage of the current, but as a secondary phenomenon, produced by the discharge. Hertz, for example, suggested that the production of the kathode rays by the discharge in a vacuum tube is analogous to the production of light by the ordinary arc discharge in air. This view furnished a ready explanation of most of the observed phenomena, such, for example, as the rectilinear propagation and diffuse reflection of the kathode rays, and the thermal, mechanical, and luminous effects produced by them. The explanation of the well-known deflection of the rays in passing through a magnetic field was, however, a matter of greater difficulty. I am not aware that a thoroughly satisfactory explanation of this phenomenon, based upon what may be called the ether theory of the kathode rays, has ever been proposed.

The theory proposed by Crookes in 1879, and which usually bears his name, differed radically from that just mentioned. By Crookes and his followers the kathode rays were thought to consist of a stream of negatively electrified particles projected at high velocity from the negative electrode. Such particles would naturally travel in straight lines; upon colliding with solid obstacles their energy would be transformed into that of heat, light, or visible motion; and when moving across the lines of force of a magnetic field they would be deflected from their straight path. The theory of Crookes possessed the great advantage of being concrete and definite, while, at the time the theory was proposed, it was in qualitative agreement with practically all the observed phenomena.

The work of later experimenters, however, had in many instances tended to discredit the theory of Crookes. Thus, the various mechanical effects produced by kathode rays, such as the rotation of radiometer wheels and the like, were found to be due largely, if not wholly, to secondary causes, such as the heat developed by the rays, and the varying static charges on the walls of the tube. Again, if the rays consist of negatively electrified particles, we should expect a conductor placed in their path to acquire a negative charge. Experiments made to test this question were contradictory, but in the majority of cases it was found that the charge was *positive* instead of negative.* Electrified particles moving at right angles to an electrostatic field should be deflected from their straight course; but experiments made by Hertz † and others to detect such an electrostatic deflection gave only negative results. Since the kathode rays are deflected in passing through a magnetic field, we should expect these rays, if they consist of material par-

* Crookes, *Phil. Trans.*, 1879.

† Hertz, *Wied. Ann.*, 19, p. 782, 1883.

ticles, to react upon the field and exert a force tending to move the magnet to which the field is due; no such reaction could be detected.* Many other instances might be cited in which the results of observation were apparently in direct contradiction with the Crookes theory.

Such, in brief, was the condition of the subject at the beginning of the present decade. Of the two theories that had been proposed, each possessed strong arguments in its favor. Neither was free from serious objection.

Previous to this time, very little work of a quantitative nature had been done in connection with the kathode rays, although several estimates had been made of their velocity. Thus, according to Spottiswood and Moulton† the velocity was considerably less than that of light; whole Goldstein‡ had reached the conclusion that the velocity was greater than one four hundredth of the velocity of light. In 1894 a direct determination of the velocity was made by J. J. Thomson§, the method being to observe two fluorescent spots, produced by the kathode rays at different distances from the kathode, by means of a revolving mirror. The result obtained was 2×10^7 cm. per second, or about one thousand times less than the velocity of light. This velocity is practically the same as that which would be acquired by a hydrogen ion repelled from the kathode. Thomson's result therefore supported the view, previously expressed by Schuster, that the kathode rays were not composed of particles of metal torn loose from the electrode, or of charged molecules of the residual gas, but that they consisted of a stream of ions such as occur in ordinary electrolysis.

Recent determinations of the velocity of the kathode rays have shown that the value obtained by Thomson was too small, so that the conclusions based upon it were incorrect. Nevertheless, I am inclined to think that they served a useful purpose. For by directing attention to the discredited emission theory, and to the probable electrolytic nature of gaseous conduction, they stimulated investigation and contributed to the advance of the subject.

The more modern phase of our subject properly begins in 1892, when it was discovered by Hertz* that the kathode rays were able to penetrate thin sheets of gold foil, aluminium, and glass. Taking advantage of this discovery, Lenard in 1893† constructed a vacuum tube containing a small opening covered with aluminium foil, through which the rays passed out into the open air, or into a second tube. It was thus possible to study the rays under conditions which could be readily varied, while the conditions under which the rays were developed remained unaltered. This form of apparatus not only made possible a more systematic study of the known properties of the kathode rays, but also led to the discovery of many new phenomena. Thus, in air at ordinary pressures, the rays were found to discharge electrified bodies, to develop ozone, and to give an impression upon a photographic plate. The photographs published by Lenard, showing the opacity of glass and quartz to these rays, and the comparative transparency of the metals, are strikingly similar to those since obtained with the X-rays. In fact, it now seems probable that X-rays were present to some extent in all Lenard's experiments, and that the phenomena observed by him were in part caused by them.

One of the first questions investigated by Lenard was the influence of the medium through which the rays passed upon their

* Hertz, l. c.

† *Phil. Trans.*, 171, p. 627, 1880.

‡ Goldstein, *Wied. Ann.*, 12, p. 101, 1880.

§ Thomson, *Phil. Mag.*, 38, p. 358, 1894.

* Hertz, *Wied. Ann.*, 45, p. 28, 1892.

† Lenard, *Wied. Ann.*, 51, p. 225, 1894.

intensity and magnetic deflection.* In passing through the air or other gases the rays were observed to suffer diffusion similar to that experienced by light in a turbid medium. It was found that the absorption and diffusion of the rays were approximately proportional to the density. The magnetic deflection, on the other hand, was independent of the medium in which the rays were observed, and remained the same even after the rays had passed through thin sheets of metal.

By changing the conditions under which the rays were generated, different kinds of kathode rays were obtained, whose penetrating power and susceptibility to the action of a magnetic field could be varied through a wide range. Thus, upon reducing the pressure in the tube where the rays were developed, the penetrating power of the rays was found to increase, while at the same time the magnetic deflection became steadily less. In connection with this work Lenard called attention for the first time to the so-called 'magnetic spectrum' of the kathode rays† a phenomenon which was rediscovered by Birkeland‡ in 1896 and has since attracted considerable attention. It appears that a beam of kathode rays is ordinarily not homogeneous, but that it consists of rays which are magnetically deflected in different degrees. In consequence, the fluorescent patch produced by such a beam, after passing through a magnetic field, is no longer sharply defined. In many cases it is drawn out into an interrupted band, in which regions of bright fluorescence alternate with regions of comparative darkness. The resemblance to a banded or bright line spectrum is often quite striking. The phenomenon is now known to be due to the employment of a fluctuating or interrupted current in developing the rays.* Since the character of the kathode rays is so largely dependent upon the conditions under which they are developed, it is natural to expect that when these conditions are unsteady the rays obtained will be non-homogeneous. If the rays are developed by a steady current, the magnetic spectrum is reduced to a single bright line.

* *Wied. Ann.*, 52, p. 23, 1894; 56, p. 255, 1895.

† *Wied. Ann.*, 52, p. 32, 1894.

‡ *Comptes rendus*, 123, p. 492, 1896.

Without stopping to discuss further the interesting and important phenomena investigated by Lenard, let us consider for a moment the bearing of his work upon the two opposing theories of the kathode rays. Upon the assumption that the rays consisted of some sort of wave motion, all Lenard's results were readily explained. That such waves should pass through air, and even through thin layers of metal, was to be expected; the same is true with ordinary light. To explain the diffusion of the rays, it was sufficient to assume that the wave length was small compared with the dimensions of a molecule. The same assumption explained the observed relation between absorption and density. The difficulty in accounting for the magnetic deflection of the rays still remained. But this difficulty was no greater than it had always been, and seemed by no means insurmountable.

On the other hand, to interpret Lenard's results in accordance with the Crookes theory, in the form that it then took, was a matter of great difficulty. That excessively short waves should be able to pass through metal is reasonable enough; but that atoms or molecules should be able to pass is hard to believe. Yet, according to Lenard's experiments, not only must these atoms pass through a grounded sheet of aluminium, carrying with them their electric charge, but they must emerge from the other side with their momentum sensibly unaltered. The suggestion was indeed made by the advocates of the Crookes the-

* Strutt, *Phil. Mag.*, 48, p. 478, 1899.

ory that the rays did not really penetrate Lenard's aluminium window, but that they made of it a secondary kathode, which sent out new rays of its own into the region beyond.* But the objections to this view are numerous. For example, it is remarkable that the secondary rays should be *exactly* similar in their properties to the rays which produced them, regardless of whether the secondary kathode is thick or thin, a conductor such as aluminium, or an insulator such as glass. Again, Lenard obtained these rays both in air at ordinary pressures, and in a vacuum so high that no discharge could be made to pass. In neither case can kathode rays be produced by any other known method. Is it not strange that a secondary kathode, forming part of a grounded metal inclosure, should not only develop these rays under conditions where all other methods fail, but that it should also produce rays of the same kind and intensity under such widely different conditions? These and other objections make it seem highly unlikely that the Lenard rays can be satisfactorily explained by treating the aluminium window as a secondary kathode. In fact, I think that this view has now been very generally abandoned. But even if it were accepted as correct, the difficulties in the way of the Crookes theory still remained. For if the kathode rays consisted of charged atoms, as had been indicated by the work of Schuster and J. J. Thomson, the fact that they were able to pass through air is scarcely less surprising than that they should penetrate thin sheets of metal.†

Lenard himself interpreted his results as offering additional support to the ether theory, and called attention to the fact that in order to explain the observed phenomena the wave-length must be small compared with the dimensions of a molecule. At the close of his first article in 1894 he says, "Judging by the observed behavior of the gases" (viz, diffusion and absorption of the rays) "the ether phenomena that constitute the kathode rays must be of such extraordinary fineness that dimensions as small as those of molecules have to be taken into consideration. Even toward light of the shortest known wave-length, matter acts as though it were continuous. But toward kathode rays, even the elementary gases behave like non-homogeneous media; each individual molecule seems to form an obstacle to their propagation. Analogous phenomena are observed when ordinary light passes through a medium made turbid by suspended particles."

When we consider the condition of the subject at that time, Lenard's conclusion that the rays must consist of something analogous to wave motion seems most natural. From our present standpoint, however, it is seen that his results might be equally well explained by a modification of the Crookes theory. The same difficulties that are surmounted by the assumption of extremely short waves can also be removed by the assumption of extremely small particles. If the kathode ray particles are only small enough, they might pass for a considerable distance through air, or even through metal films; upon colliding with the molecules of a gas they would rebound in all directions, and diffusion would result; and both diffusion and absorption would be roughly proportional to the density of the medium. But this requires that particles of matter should exist which are small as compared with atoms. The suggestion is a startling one, and so violently contradicts our ordinary views of the constitution of matter that it cannot be accepted without strong support. It is not surprising, therefore, that several years

* J. J. Thomson, 'Recent Researches in Electricity and Magnetism,' p. 126. 'Discharge of Electricity through Gases,' p. 190.

† See J. J. Thomson, 'Discharge of Electricity through Gases,' p. 196.

elapsed after the discovery of the Lenard rays before this modification of the Crookes theory was proposed.

In 1895, about a year after the publication of Lenard's results, came the discovery of the X-rays by Röntgen. The widespread interest which this discovery aroused is fresh in the minds of all of us, and is probably without a parallel in the whole history of physics. Apart from their importance from a purely scientific standpoint, and from their sensational features, the X-rays occupy a unique position among the phenomena connected with the electrical discharge in vacuum tubes; for they afford the first instance in which the scientific results obtained in this branch of physics have been made directly useful in everyday life. Although it is not the purpose of the pure scientist to seek directly such applications, yet every instance of this kind is always a source of gratification. Each new case serves to strengthen that belief which forms the real basis of scientific investigation; the belief that every advance in our knowledge of natural law, be it ever so small, or ever so removed in appearance from the affairs of everyday life, must ultimately contribute to the increase of human happiness and the progress of mankind.

The discovery of the X-rays served to stimulate investigation along all related lines. Interest in the phenomena of the electrical discharge through gases, and especially in the kathode rays, became stronger than ever before; for it was natural to expect that the puzzling problem of determining the nature of the Röntgen rays might be simplified by a better understanding of the kathode rays that produced them.

The numerous difficulties and apparent contradictions which had stood in the way of the adoption of the Crookes theory have already been referred to. These may be said to have culminated with the discovery of the Lenard rays, and the theory in its earlier form was of necessity abandoned. But since that time the difficulties have been one by one removed. Thus, in 1896, it was shown by Perrin* that the kathode rays really do carry a negative charge; this conclusion was confirmed by J. J. Thomson† in 1897. That a negative charge is also carried by the Lenard rays was afterwards shown by McClelland,‡ Wien,§ and Lenard.|| By passing the rays through an aluminium window in a completely closed metal box, Lenard was able to give a negative charge to an insulated conductor within. Certainly a more conclusive proof that the kathode rays are electrified can hardly be demanded.

The deflection of the kathode rays in passing through an electrostatic field, which the Crookes theory required, and which Hertz had looked for in vain, was proved to exist by Jaumann ¶ in 1896, and much more conclusively by J. J. Thomson ** in 1897. A year later it was shown by Wien †† and Lenard ‡‡ that a similar electrostatic deflection occurred in the case of the Lenard rays.

Not only were the earlier experiments shown to be in error in both these cases, but the reasons for their failure are now pretty well understood. Probably the most important sources of error were due to the fact that the residual gas in a vacuum tube is rendered conducting by the discharge. The kathode rays also exert a special ionizing influence of their own, so that in those parts of the tube which are traversed by these rays, the gas becomes temporarily a good conductor. In consequence it acts

* Perrin, *Nature*, 53, p. 298, 1896.

† Thomson, *Phil. Mag.*, 44, p. 293, 1897.

‡ McClelland, *Lond. Elect.*, 39, p. 74, 1897.

§ Wien, *Wied. Ann.*, 65, p. 440, 1898.

|| Lenard, *Wied. Ann.*, 64, p. 279, 1898.

¶ Jaumann, *Wiener Berichte*, 105, 2a, p. 291, 1896.

** Thomson, *Phil. Mag.*, 44, p. 293, 1897.

†† Wien, *Wied. Ann.*, 65, p. 440, 1898.

‡‡ Lenard, *Wied. Ann.*, 64, p. 279, 1898.

as a conducting screen, which protects the rays from electrostatic influences. This explanation of the failure to obtain electrostatic deflection was suggested by Schuster * as early as 1890; but the importance of this source of error was not generally appreciated until much later. The fact that a conductor placed in the path of the kathode rays usually takes a positive charge instead of a negative one is doubtless due to the same cause. Being surrounded by a conducting medium, the conductor will receive its charge partly from the kathode rays and partly by induction. The inductive charge will usually be positive, and may be sufficiently strong to determine the sign of the resultant. Doubtless the almost universal employment of the induction coil by the earlier observers was also in part to blame for the contradictory results. The use of a fluctuating current is now seen to introduce many annoying complications. In quantitative work especially, some source of steady current, such as a large Holtz machine or a storage battery, is much to be preferred.

The discovery that the kathode rays carry a negative charge and are subject to electrostatic deflection afforded so strong an argument in favor of the Crookes theory, that attempts were at once made to subject the theory to quantitative tests. The question of the size of the kathode ray particles and the charge carried by them was attacked independently and almost simultaneously by Wiechert† and J. J. Thomson.‡ It is interesting to observe that although the conclusions reached were practically the same, the methods employed were radically different. Wiechert's first determinations were based upon the consideration that since the motion of the kathode ray particle is due to the electrical forces, the kinetic energy acquired by each particle must be equal to the potential energy which it possessed at the surface of the kathode. A relation is thus obtained connecting the charge, mass, and velocity of the particles with the potential of the kathode. A second relation between these same quantities is obtained by measuring the deflection of the rays in a magnetic field of known strength. By elimination it is then possible to determine both the velocity of the rays and the ratio of the charge carried by each particle to its mass. The results indicated a velocity not far from 10^{10} cm. per second, or nearly one-third that of light. That a material particle should move at such an enormous velocity seems almost incredible. It is not surprising that Wiechert felt the need of checking this result by some independent method. He did so by employing a method that had been suggested by Des Coudres* in 1895, and which is independent of any assumption regarding the nature of the kathode rays; the results obtained were of the same order of magnitude as before. That the kathode rays often have a velocity closely approaching that of light has since been abundantly confirmed.

Wiechert's values for the ratio e/m—*i. e.*, the ratio of the charge carried by a kathode rays particle to the mass,—lay between 20×10^6 and 40×10^6 (c. g. s., electro-magnetic units). This is about three thousand times greater than the corresponding ratio for the hydrogen ion in ordinary electrolysis. We must therefore conclude either that the particles carry a much larger charge than is carried by an ion in electrolysis, or else that they are smaller than the hydrogen atom. The latter alternative, which harmonizes so well with the

Proc. Roy. Soc., 47, p. 526, 1890.

† Physikal.-ökonom. Gesellschaft in Königsberg. Jan. 7, 1897. *Wiedemann's Beiblätter*, 21, p. 443.

‡ Royal Institution Lecture. April 30, 1897. *Lond. Elect.*, 39, p. 104, 1897. *Phil. Mag.* 44, p. 293, 1897.

* *Wiedemann's Beiblätter*, 21, p. 648.

phenomena of the Lenard rays, is the one usually accepted.

The value of e/m was determined by two entirely different methods by J. J. Thomson, the results being published at practically the same time as those of Wiechert. In the first method used by Thomson, the kinetic energy of the particles was determined by measuring the heat developed when the rays fell upon the face of a thermopile, and the charge carried by them was measured by an electrometer. These two measurements, together with the magnetic deflection in a known field, make possible the computation of both e/m and v. The values of e/m obtained in the most reliable experiments by this method ranged from 14×10^6 to 10×10^6. The corresponding values of the velocity were about one-tenth the velocity of light. The second method, which is regarded by Thomson as more reliable, involved the determination of the electrostatic deflection in a known electric field, and the magnetic deflection of the same rays in a known magnetic field. This method gave values of e/m ranging from 9×10^6 to 6.7×10^6, the velocity being about one-tenth that of light, as before. Thomson found that the ration e/m was independent of the nature of the gas in the tube. This result has been confirmed by Kaufmann,* who found that the ration was also independent of the material of the kathode.

The conclusions naturally drawn from these results may be put into the following crude and provisional form: The kathode rays consist of negatively charged particles, or corpuscles, which are much smaller than the atom of hydrogen. These corpuscles are present as a constituent part of the molecule in all substances: whether only one such corpuscle is present for each molecule, possibly revolving about it like a satellite, or whether each molecule consists of an aggregation of corpuscles, it is not yet possible to say. Under the influence of the intense electrical field at the negative terminal of a vacuum tube, the corpuscles are in some cases freed from the forces that hold them to the remainder of the molecule, and shoot off at enormous speed to form the kathode rays.

* *Wied. Ann.*, 61, p. 545, 1897.

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(*To be concluded.*)

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*SOME TWENTIETH CENTURY PROBLEMS.**

IT is never a bad plan to improve an anniversary occasion by comparative observations. In commercial and manufacturing lines, short intervals of time are marked by balancing books and checking off accounts, and an inventory is taken at the end of the year without exception. And so it happens that I am going to recognize to-day the fact that we stand at the end of a century, and what I have to say will be influenced to no small extent by the recognition of that fact.

Under ordinary circumstances, with this in mind, I could hardly avoid following the commercial example at the end of the year, and taking an account of stock, balancing accounts, and ascertaining the advance or retrogression in our branch of the scientific world during the period of time that represents three generations of human beings. I do not intend, however, to do this, partly because I do not wish to weary an audience with all that ought to be passed in review in such an important anniversary summation, and partly because, a few years since, Professor H. Marshall Ward, in resuming the botanical progress of the Victorian Era, gave the more important facts, while the vice-presidential addresses of several recent years before this Section have dealt with important advances in botanical thought in

*Address of the Vice-President, Chairman of Section G (Botany) of the American Association for the Advancement of Science, given at the New York meeting.